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Laser-doped metal-plated bifacial silicon solar cells

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ABSTRACT

In this paper we report on the fabrication of laser-doped p-type bifacial cells using self-aligned metal-plating with energy conversion efficiencies as high as 19.2%. A key fabrication step for these cells is recognising that the p-type silicon regions can be made cathodic by forward biasing the p–n junction in a process which we call here field-induced plating (FIP). Used in conjunction with light-induced plating (LIP) in the same plating apparatus, FIP can be used to form low cost nickel/copper grids on both surfaces of a cell. Furthermore, the simplicity of the FIP process means that it can potentially be performed using the same plating equipment and chemistry as used for LIP. Plating rates similar to LIP were achieved (i.e., ~10 μm of copper in 10 min), however there is potential to plate at much faster rates with FIP because the junction is forward-biased. This bifacial cell plating method could be adapted to metallise a range of bifacial cells including heterojunction cells.

1. Introduction

The power output of bifacial solar cells can be boosted by albedo radiation, however these cells can be expensive to manufacture if screen-printed silver (Ag) grids are used on both surfaces of the cell. Plated nickel (Ni)–copper (Cu) metallisation can reduce the metallisation cost by replacing the need for screen-printed Ag (see [1–3]). Electroless plating of Ni/Cu was used to metallise BP Solar's laser buried grid (also known as "buried contact") cells [4–6], and has been used to fabricate bifacial buried contact cells [7], however this plating process is slow and plating bath maintenance is expen sive [1]. The use of light-induced plating (LIP) can address these issues with 10 μm high Cu conductors being plated in ~10 min rather than the ~3 h required for electroless plating, and bath maintenance is simplified by the use of corroding anodes to replace and maintain a constant metal ion concentration in the bath. Light-induced plating has been used to fabricate cells with full-area back surface fields (BSFs) with efficiencies up to 19.7% [8] and cells with localised BSFs with efficiencies of 21.0% [9]. However, LIP can only be used to metallise n-type regions of the cell. Although electroplating has been successfully used to metallise interdigitated back contact cells [10,11], this process requires the presence of a seed layer and necessitates that the region to be plated is directly contacted by the cathode. For bifacial cells this would require the busbars of the metal grids to be directly contacted by the plating tool.

We report here a new plating method which can be used to metallise p-type silicon regions. This method, called field-induced plating (FIP), involves forward-biasing the p–n junction such that exposed p-type silicon regions become cathodic and able to be plated. The method, which shares the chemical simplicity of LIP, can potentially be performed using the same equipment as used for LIP and does not require a seed layer and specific aligned contacting of the busbars of the grid. Although plating with the solar cell under forward bias has been recently reported by others [12,13], the more general method we present here can be used to plate cells where both surfaces of the cell are protected by dielectrics. Used in conjunction with LIP, FIP can enable the plating of bifacial silicon solar cells. In this work we apply LIP and FIP to the metallisation of bifacial p-type cells (see Fig. 1) where the contact regions have been formed using phosphorus (P) [8,9,14–17] and boron (B) [18,19] laser doping. This plating method can be applied to other bifacial cells including heterojunction cells where metal is plated directly to the transparent conductive electrode.

2. Field-induced plating

In FIP, the p–n junction of a solar cell is forward-biased by the placement of electrodes in the plating bath. A single side immersion technique was used in this work so that only the p-type

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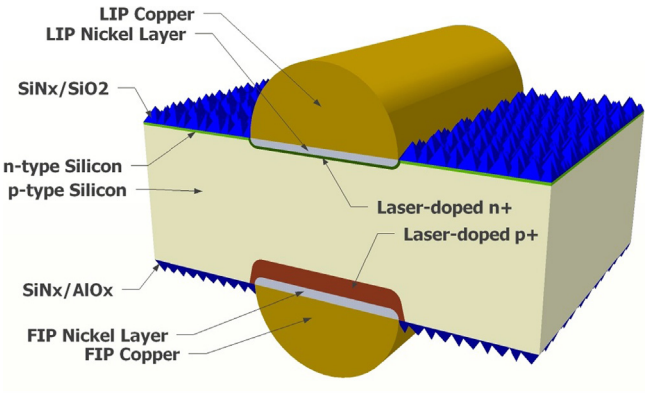

Fig. 1. Schematic diagram of a p-type bifacial metal-plated laser-doped silicon solar cell.

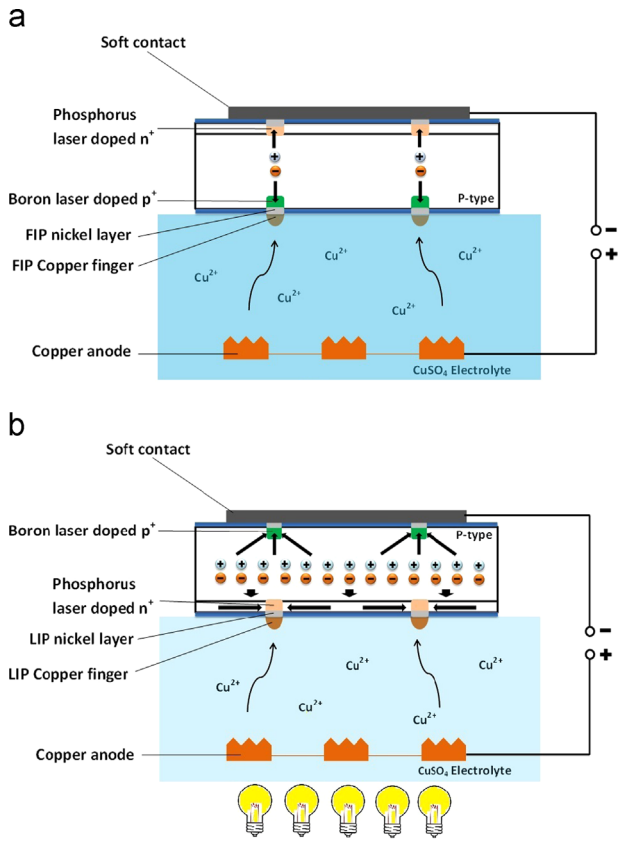

Fig. 2. Schematic diagrams of: (a) the FIP process; and (b) the LIP process, showing how the current flow through the cell differs.

surface of the cell was in contact with the plating electrolyte (see Fig. 2(a)) and a "soft contact" graphite electrode was used to enable electrical contact between Si exposed in the laser-doped grooves and the external circuit. A metal anode, placed under the cell at the base of the bath, corroded to provide a source of metal ions for plating. Since the cell is forward-biased in FIP, large plating currents are possible, however currently plating rates for Cu are limited to ~1 μm/min primarily because the Cu plating formulations used were designed to operate within this rate range.

The flow of current through the cell is enabled by openings in the dielectric layers as shown in Fig. 2(a). In the work reported here, the dielectric layer openings have been formed by laser-doping, however other methods of forming openings can also be used. The soft electrode enables electrical contact to the silicon exposed though the laser-doped openings. Although expanded graphite was used as the electrode material, other soft contact methods can also be used. The plating apparatus shown in Fig. 2 can be used to perform both LIP and FIP. In LIP the soft electrode can be used to deliver the bias voltage to the p-type surface of the cell and a light source is provided under the cell (through the plating electrolyte) to metallise the n-type grid. To perform FIP the cell must be inverted so that the n-type grid is in contact with the soft electrode (cathode) and the p-type grid is exposed to the electrolyte. In both arrangements the anode remains in the bath to replenish and maintain the metal ion concentration. It is therefore foreseeable that a single multi-lane plating tool could achieve both processes and therefore enable high throughput plating in manufacturing.

It is useful to consider how the current flows in FIP (see Fig. 2(a)), in comparison to LIP (see Fig. 2(b)), for bifacial cells. In LIP, the light-generated carriers are collected uniformly in the n-type emitter of a cell and then travel laterally to the contact regions. As long as the laser-doped lines are appropriately deglazed to remove any oxide which may exist at the surface (e.g., see [20]), uniform plating to the n-type laser-doped grid is readily achievable. However when FIP is used to metallise bifacial cells, the current flows directly from the n-type to the p-type contact regions. This means that plating uniformity is enhanced if the n-type and p-type grids are aligned with each other.

Forward-biasing of the solar cell diode has been used to plate the p-type grids of heterojunction cells [12] and boron-doped n-type silicon cells [13], however in these reports the cathode contacted the already metallised n-type surface of the cell and consequently no soft contacting mechanism was required. However, by using the cell contacting mechanism described in this paper, bifacial cells with both surfaces masked can also be plated using FIP in conjunction with LIP. The soft electrode arrangement described here for plating has also been applied to field-induced anodisation (FIA) [21,22] and an adaptation of the soft contact has been used for a recently reported light-induced anodisation (LIA) which has been demonstrated to form very uniform SiO_2 [23] and anodic aluminium oxide layers [24].

3. Experimental

156 mm alkaline-textured B-doped 1–3 Ω cm Czochralski (Cz) silicon wafers were diffused to an emitter sheet resistance of 80–100 Ω/□ in a $POCl_3$ furnace. After phosphosilicate glass (PSG) removal, a single-side wet chemical etching process was performed to remove the rear junction then a ~10 nm SiO_2 layer was thermally-grown on both wafer surfaces using dry oxidation and 75 nm of SiN_x (refractive index ~2.0) was deposited on the n-type surface by plasma-enhanced chemical vapour deposition (PECVD) using a Roth & Rau MAiA tool.

The rear surface of one group of cells was then passivated by deposition of 200 nm SiN_x (Roth & Rau MAiA) over the thin SiO_2 layer (SiO_2/SiN_x rear passivation). The other group of cells was passivated by depositing a 10 nm AlO_x and then 200 nm SiN_x (Roth & Rau MAiA) (AlO_x/SiN_x rear passivation) over the existing SiO_2 layer. The 156 mm wafers were then laser-cleaved into wafer fragments of ~4 cm × 4 cm to complete the processing.

Laser doping was performed using a 15 W 532 nm laser using 85% phosphoric acid and PBF1 B spin-on source (from Filmtronics) to form the n+ and p+ grids, respectively. The P laser-doping process was performed as described in [25], however a series of experiments were performed to ascertain the optimum B laser-doping parameters. The final cell area and exposed silicon grid area were 6 cm^2 (i.e., smaller than the initial wafer fragment size due to the need to use a mask during the laser doping process to